Principles of Array System Design

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1. Introduction

Receiver coil arrays, first introduced in the late 1980's [1,2], have become the preferred MR imaging coils over volume coils due to their ability to provide high SNR and wide anatomical coverage simultaneously. Recent cost reductions in analog-to-digital conversion technology and computing power have enabled an increase in the number of receiver channels available in the current clinical imaging systems to 16 or 32. Array coils and independent receiver chains also enable parallel imaging techniques [3,4] which make use of the additional spatial encoding provided by the receive sensitivities of the array elements to scan more efficiently.

The parallel imaging performance of an array is closely related to the uniqueness of each element's sensitivity pattern. For such applications (indeed most arrays today are used for parallel imaging at least some of the time) the design process begins by choosing the number, shape and arrangement of the elements, followed by electromagnetic field modeling to predict sensitivity patterns and the noise covariance matrix needed to calculate parallel imaging performance, e.g., the geometry factor [3]. Optimization can then be performed [5,6]. In general the resulting array is different from that obtained by designing for optimal SNR in conventional imaging [2,7], especially if the number of coils is limited [8].

2. The Receive-Only Surface Coil

Once the geometrical part of the design is decided we can begin designing the electronics. It is useful to recall some principles of receive-only surface coil design given the many features in common with the single elements of the array.

2.1 Transmit detuning

Each element of a coil array is a surface coil designed to receive the signal from the nuclear spins. During RF excitation pulses, usually provided by a body transmit coil, the receiver coil must be "transparent", i.e., it must not distort the B_1^+ profile of the volume coil. This can be achieved by limiting the currents on the coil induced by the transmit field to negligible levels by ensuring that the total impedance of the coil loop is sufficiently high [9]. This, unfortunately, is far from true for a coil that is resonant at the NMR frequency.

The total impedance of the coil must therefore be switched from low in the receive state, to high in the transmit state. There are two approaches to achieving this: active detuning and passive detuning. The simplest is passive detuning, which relies on the transmit field's ability to forward bias a pair of crossed high-speed diodes [10]. In the most common configuration the diodes act as a switch that connects a parallel resonant trap to the coil thus opening the circuit. This method is seldom used except as a redundant safety feature because if the transmit field is not intense enough the diodes will not be fully switched on and the strong interaction between transmit and receiver coils will persist.

Active detuning is more reliable but requires bringing an external DC bias voltage to diodes on the coil [9]. The switching devices most often used today are PIN diodes, i.e., a silicon

PN junction separated by a thin layer of intrinsic semiconductor. This construction increases the carrier lifetime and allows the diode to control large RF currents with a small DC current and low RF resistance. The additional logic signal required to switch the coil between transmit and receive states is supplied by the spectrometer either on a dedicated line or using the power RF amplifier's unblank signal.

2.2 Noise matching to preamplifier

Thermal noise is generated in all lossy components, as well as within the preamplifier itself, and is characterized by the noise factor *F* (or noise *figure*, $NF = 10\log F$, when expressed in decibels (dB)), the ratio of output to input SNR. The first stage of amplification is the most critical since the noise factor, *F*, of a cascade of signal transmission stages (not necessarily amplification) is calculated from the individual noise factors, F_i, and gains, G_i, as [11]

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + ...$$

This relationship also implies that any noisy circuit placed before the preamplifier will have a great impact on the achievable noise performance. Consequently the connection between the coil and preamp (i.e., the matching circuit) must be given careful consideration. Low-loss components such as air-wound inductors are recommended and using cables between the coil and preamp is strongly discouraged. Avoiding cables also facilitates matching since the necessity to match to the characteristic impedance of the cable at both ends is eliminated.

Matching is required because the preamplifier will achieve its best noise performance only when at its input it sees an impedance equal to Z_{opt}, which should be obtained from technical documentation or bench measurements. For FET input stages Z_{opt} is of the order of a few hundred ohms. If the impedance at the input, Z_s, is not equal to Z_{opt} the noise factor will be degraded according to [11]

$$F = F_{MIN} + \frac{R_n}{Z_0} \frac{|\Gamma_S - \Gamma_{OPT}|}{(1 - |\Gamma_S|^2)|\Gamma_S + \Gamma_{OPT}|^2},$$

where R_n is the preamp's correlation resistance and the Γ's are reflection coefficients calculated using impedance Z_0 (usually 50Ω) as a reference:

$$\Gamma = \frac{Z - Z_0}{Z + Z_0}.$$

In case the noise parameters of the preamp are not known it is nevertheless possible (albeit tedious) to vary the coil-preamp matching and measure the SNR using an imaging sequence until an optimal configuration is found.

3. Surface Coil Arrays

3.1 Coil Decoupling

Creating an array is not as simple as putting together a number of elements described above mainly because of inductive coupling, which causes changes in the frequency response of the elements and degrades their sensitivity. Coupling also reduces the spatial uniqueness of the signals acquired from the coils, although there has been some debate recently questioning the necessity of strictly minimizing signal coupling to achieve optimal SNR and parallel imaging performance [12,13].

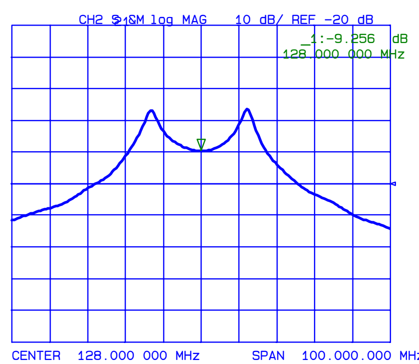
A coupling of −20dB or lower is considered good for most applications, and values around −10dB are common for closely coupled coils. The lowest achievable coupling (i.e., eliminating the inductive component) is determined by the coils' mutual resistance through the loading phantom [14,15] (giving rise to noise correlation) as well as parasitic capacitances, especially at higher frequencies.

3.1.1 Geometric decoupling

This method takes advantage of the fact that when two coils are overlapped there exists a separation where the mutual inductance is zero [2,16]. At this overlap the coupling between the coils is minimal and given only by parasitic capacitance and mutual resistance through the sample. While this technique has the advantage of being broadband, unfortunately it cannot be extended beyond three coils [7], and therefore additional techniques have been developed. Furthermore, parallel imaging techniques are known to sometimes achieve better spatial encoding if the coil elements are not overlapped [6].

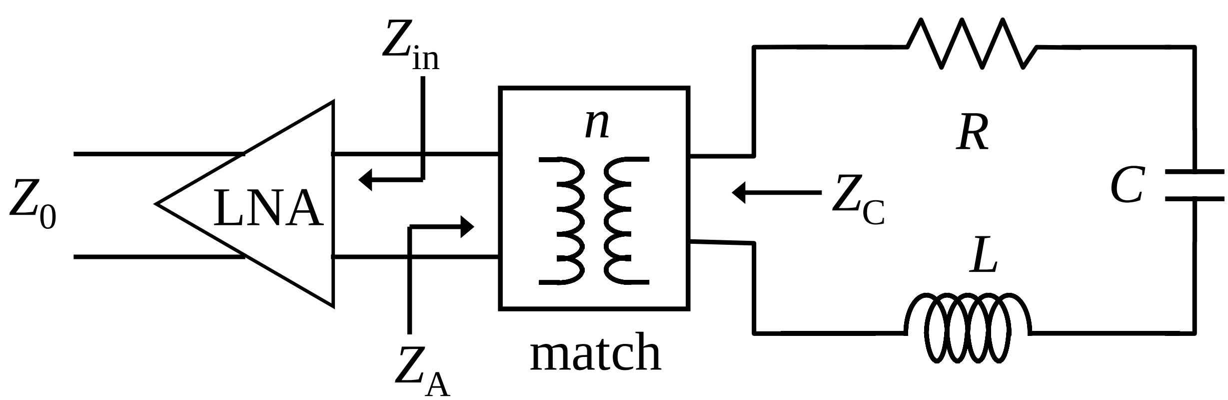
3.1.2 Preamplifier decoupling

Preamp decoupling uses preamplifiers with either a very large or very small input resistance (more generally a large input reflection coefficient). This additional demand on preamplifier performance is not easy to achieve while maintaining good stability and noise characteristics, especially at higher frequencies. An important advantage of preamp decoupling is its robustness against changes in geometry. Arrays on flexible or adjustable formers are therefore possible without requiring electrical adjustments each time a mechanical adjustment is made.



Preamp decoupling is achieved by creating a large impedance at the coil's ports [2] with the aid of a matching network [17], thus limiting the current flowing in the coil and therefore the amount of signal coupled to other coils. A typical frequency response of a preamp decoupled coil, with its characteristic double resonance due to the coupling of two resonant circuits (coil and matching network), is shown here. The MR frequency (marked ∇) must be in the flat part of the frequency response.

Achieving optimal noise matching and good preamp decoupling are often conflicting goals and some compromise between the two may be required. Consider the following circuit.



Equations for the circuit at resonance are

$$Z_C = Z_{in}/n^2$$
$$Z_A = n^2 R \quad ,$$

where n is the voltage transformation ratio of the matching network, $R = \omega L/Q$ is the resistance measured with the coil loaded and Q is the quality factor. The conditions for noise matching and preamp decoupling are, respectively,

$$Z_A = Z_{opt}$$
$$Z_C \gg R \quad .$$

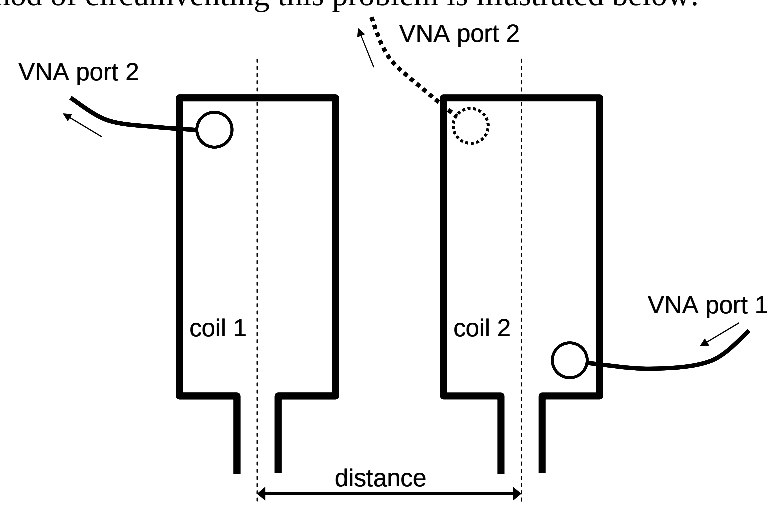
It is readily shown that there exist situations for which these conditions cannot be satisfied simultaneously. For example, if Z_{opt} = 400 Ω and R = 4 Ω then we need n^2 = 100 to satisfy the noise matching condition. If the amplifier's Z_{in} = 1500 Ω then Z_C = 15 Ω which is not » R. Besides the difficult option of obtaining a better preamplifier (with a larger Z_{in}) the only way to improve preamp decoupling is to accept a larger noise figure.

3.1.3 Reactive decoupling

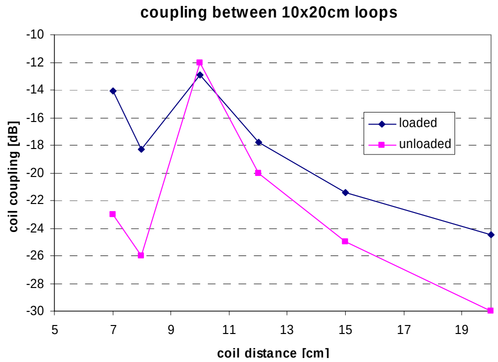
If the coupling matrix is known it is possible to design networks of capacitors and inductors that introduce couplings that are equal but opposite to those present between the coils [18,19]. This technique has proven particularly advantageous where preamp decoupling is not feasible (e.g., transmit-receive arrays) and at high fields. However, changes in coupling with time, position, loading, etc. are not easily accommodated.

3.2 Measurement of coil coupling

The direct measurement of coil coupling in a receive-only array using a network analyzer (S_{21} measurement) is not possible due to the presence of the preamplifier (a non-reciprocal device). One method of circumventing this problem is illustrated below:



An initial reference measurement is taken by driving a current in coil 2 with a shielded loop probe connected to the network analyzer's transmitting port (usually #1) and receiving (dotted probe) with the other port. It is important that the probes be attached rigidly to the coils throughout the measurement. The subsequent measurements are taken with the second probe coupled to coil #1 while the distance between the coils is varied. Results for two 10cm × 20cm loops (below) show the expected increase in coupling as the coils are brought closer, with a maximum when they are nearly touching. In this situation the coupling is maintained low by the preamplifier on coil #2. An overlap of 2cm results in greatly reduced coupling due to the cancellation in mutual inductance (geometric decoupling). Loaded and unloaded refers to the presence of a loading phantom underneath the coils.



A more practical method is to measure the noise correlation between channels, e.g., by acquiring a sufficient number [20] of noise samples with the coil array connected to the MR system and calculating the correlation between data in different channels. A relationship exists between the noise correlation and electrical coupling parameters (S parameters) [21,22], thus allowing for comparisons between the two methods.

4. Cabling and Safety Issues

Cabling and related grounding are critical parts of any array. Poor cabling can create additional coupling between the channels, as well as B_1^+ distortion and heating hazards due to currents flowing on ground conductors during transmission. This is especially important at higher frequencies where parasitic coupling between coils can create low-impedance loops that pick up RF energy. Proper cable routing is the first step to avoid these problems: one method is to route cables along regions of low electric fields (virtual grounds) [2]. Such regions can also be created by using additional conductive guard rings [23].

Remaining problems are solved by introducing cable traps near the coils [24] and/or sleeve baluns along the cables [25] to block shield currents that would otherwise flow on the outside of the shields of the coaxial cables. An easy bench test for shield currents is to grasp the coaxial cable with your hand and see if the frequency response or Q of the coil changes. On the bench one may also use clip-on ferrite cores to determine the optimal positioning of baluns. Traps must be positioned to avoid contact with the patient since the significant currents that may be present can create heating and consequently a burn danger.

5. Outlook

Developments in coil array technology is continuing in several directions. Arrays with larger numbers of elements are continuously being developed, as are applications in very-high field systems. Each of these will benefit from wireless [26] or fiber optic connections [27] to the system by reducing the bulk of cables required and enhancing safety. Theoretical investigations into the effects of noise from the electronics as coil size diminishes and frequency increases [8] have also been undertaken and await experimental confirmation. Miniaturization of the preamplifier and other electronics associated with each coil will also be required to crowd many elements into a small space.

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